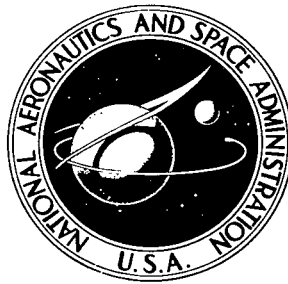


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A GRAPHIC METHOD FOR DETERMINING THE ABSOLUTE ATTITUDE OF SOUNDING ROCKET VEHICLES

by Charles F. Miller, Jr.

*Goddard Space Flight Center
Greenbelt, Md.*



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A GRAPHIC METHOD FOR DETERMINING
THE ABSOLUTE ATTITUDE
OF SOUNDING ROCKET VEHICLES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

The direction in which a rocket vehicle points during flight is its attitude. Measurements have shown that a rocket axis may trace out a complex attitude sequence. Using measureable parameters, the method outlined here plots these three-dimensional phenomena in two dimensions. The sun and its position, and the magnetic flux vector and its position, are used in combination with the solar and magnetic aspect angles at the rocket to determine attitude. When the time sequence of rocket attitudes has been plotted, the momentum vector can be accurately determined. With any known rocket position, any other portion of the sky can, by coordinate transformation, be mapped from that orientation. This method has been corroborated by a FORTRAN program.

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A GRAPHIC METHOD FOR DETERMINING THE ABSOLUTE ATTITUDE OF SOUNDING ROCKET VEHICLES

by

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Goddard Space Flight Center

INTRODUCTION

At present, the natural derivatives used for coordinates in the determination of the attitude of a rocket vehicle are the sun or moon in association with the earth's magnetic field.

Optical aspect sensors, which measure the angle between the rocket's longitudinal axis and the sun (solar aspect angle) or moon once each spin cycle, plus the fluxgate magnetometer, which measures the magnetic aspect angle of the rocket axis with respect to the local field vector, are commonly used on sounding rockets. The angle between the solar (lunar) aspect angle and the magnetic aspect angle, designated the phase angle, is also a measurable parameter on telemetry records.

The sun and magnetic south point positions are plotted, then the solar and magnetic aspect angles relative to the rocket are used to determine the azimuth and zenith distance of the rocket's longitudinal axis.

When the time sequence of rocket positions in flight has been plotted, the momentum vector can be determined.

With any known rocket position, any other portion of the sky can be mapped for that orientation by coordinate transformation.

The current three-dimensional system will first be explained, then the three-dimensional parameters will be reduced to polar coordinates. As an example, the complete flight of Nike-Apache, Flight No. 14.363 GT is then analyzed by the graphic method. Finally, confirmation of the graphic method is made using a FORTRAN program.

THREE-DIMENSIONAL PARAMETERS DEFINED

The three-dimensional, or horizon system, can be used at any latitude and longitude of ground position. It has three coordinates. The azimuth is defined as that angle from true north, measured in degrees around the horizon clockwise to a point directly below the rocket—or to the base of a vertical circle through the rocket.

In Figure 1 the vertical circle is represented by a vertical wooden protractor in a plane consisting of the zenith and the longitudinal axis of the rocket vehicle.

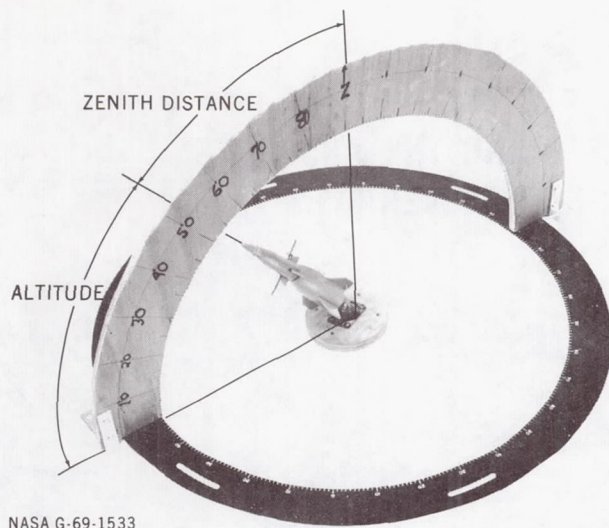


Figure 1—Horizon coordinate system showing rocket's azimuth as 249° , altitude as 52° and zenith distance as 38° .

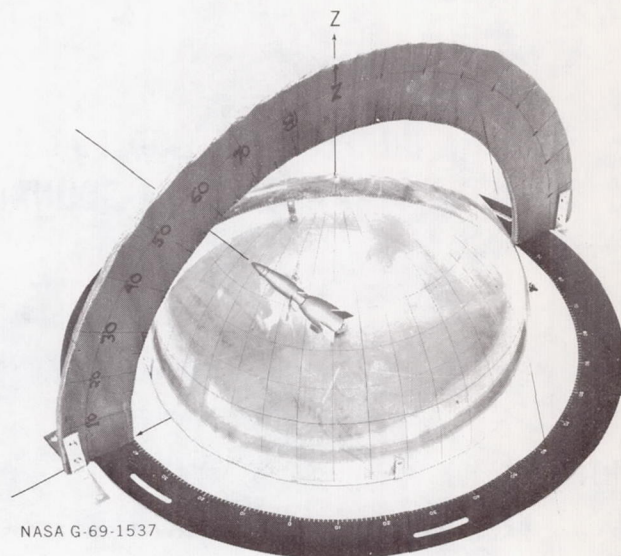


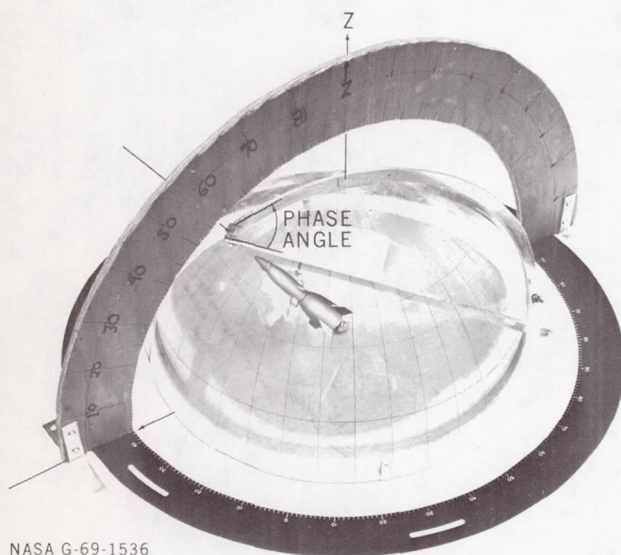
Figure 2—The horizon coordinate system with a plastic hemisphere representing the sky and marked in altitude and azimuth.

The altitude of the rocket is defined as that number of degrees (0 to 90) on the vertical circle from the horizon to the axis of the rocket. The zenith distance is defined as that number of degrees between the zenith, directly over the center of gravity of the rocket, and the longitudinal axis of the vehicle; it is the complement of the altitude. The angle can be represented by the zenith line and the longitudinal axis at the intersection, or by the arc at a fixed radius from the origin. In this paper, angles will be presented as arc distances.

The sky, or celestial sphere, may be represented by a spherical shell. As our main interest is in positions above the horizon, a plastic hemisphere is used. It is used in astronomy and navigational problems to plot stellar positions.

In Figure 2 a plastic hemisphere representing the sky has been placed over the rocket model. On this hemisphere the lines of altitude and azimuth have been plotted every 10° . The position of the nose of the vehicle is plotted in altitude and azimuth on the plastic hemisphere. The position of any other celestial body can be plotted in like manner.

The rocket's longitudinal axis represents the reference line for rocket aspect angle measurements. The rocket's center of mass locates the center of the base of the plastic hemisphere. From that rocket point three angles are measured: First, the solar aspect angle, the number of degrees which the sun's ray makes with this longitudinal axis; second, the magnetic aspect angle, the number of degrees between the longitudinal axis and the local magnetic flux vector; and third, the dihedral angle between the two planes defined by both the solar aspect angle and the magnetic aspect angle. This final angle is the phase angle between the sun and the magnetic south point. This is illustrated in Figure 3 where a hinged protractor, concentric with the rocket's center of mass, is so situated that the hinge is aligned with the rocket's longitudinal axis; one leg lies in the plane



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Figure 3—Aspect angle protractors aligned with sun and magnetic south point, and generating phase angle.

of the incident sunlight and the other lies on the plane of the magnetic flux vector, i.e., over the south magnetic point. The phase angle is and can be measured between the protractor's two halves.

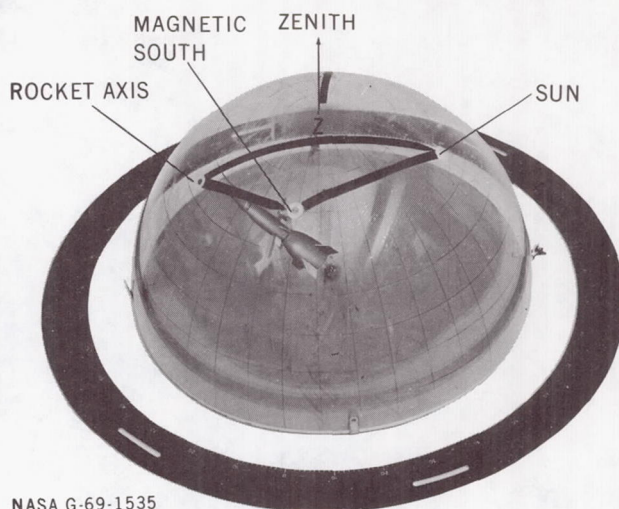
In Figure 4, black areas indicate the solar and magnetic aspect angles. The zenith is marked Z. From the magnetic south point to the sun, a black arc completes the spherical triangle. This triangle is used to determine the zenith distance and azimuth of the nose of the vehicle.

To reduce this three-dimensional system, another photograph of Figure 4 was taken directly over the zenith. The shadow of the rocket can be seen underneath the plastic hemisphere.

Notice in Figure 5 how closely the photograph represents the projection of the horizon system down to the plane of the horizon. The altitude is a cosine function of the radius from Z, thus the first 15° of altitude are hardly separable in the photograph. Figure 5 is the nearest to the two-dimensional representation to be explained next, but it is not quite as useful.

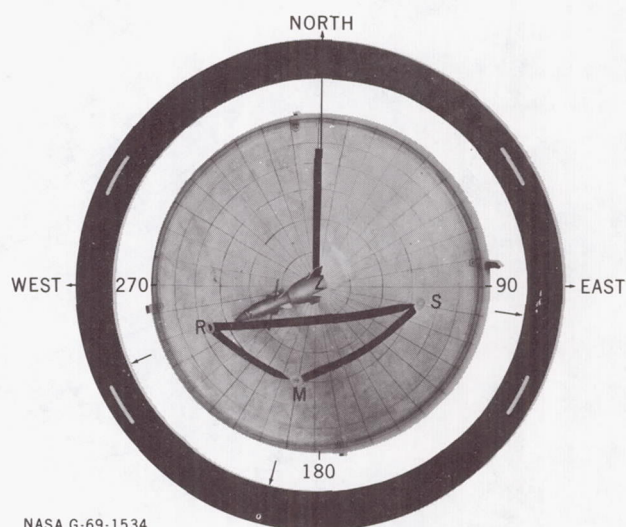
REDUCTION TO POLAR COORDINATES

The spherical parameters are now to be transformed to the two coordinates of polar graph paper. A plot is made on polar graph paper of the horizon system: the sky from the horizon to



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Figure 4—The spherical triangle needed to find zenith distance and azimuth of rocket's longitudinal axis.



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Figure 5—Zenith view of Figure 4.

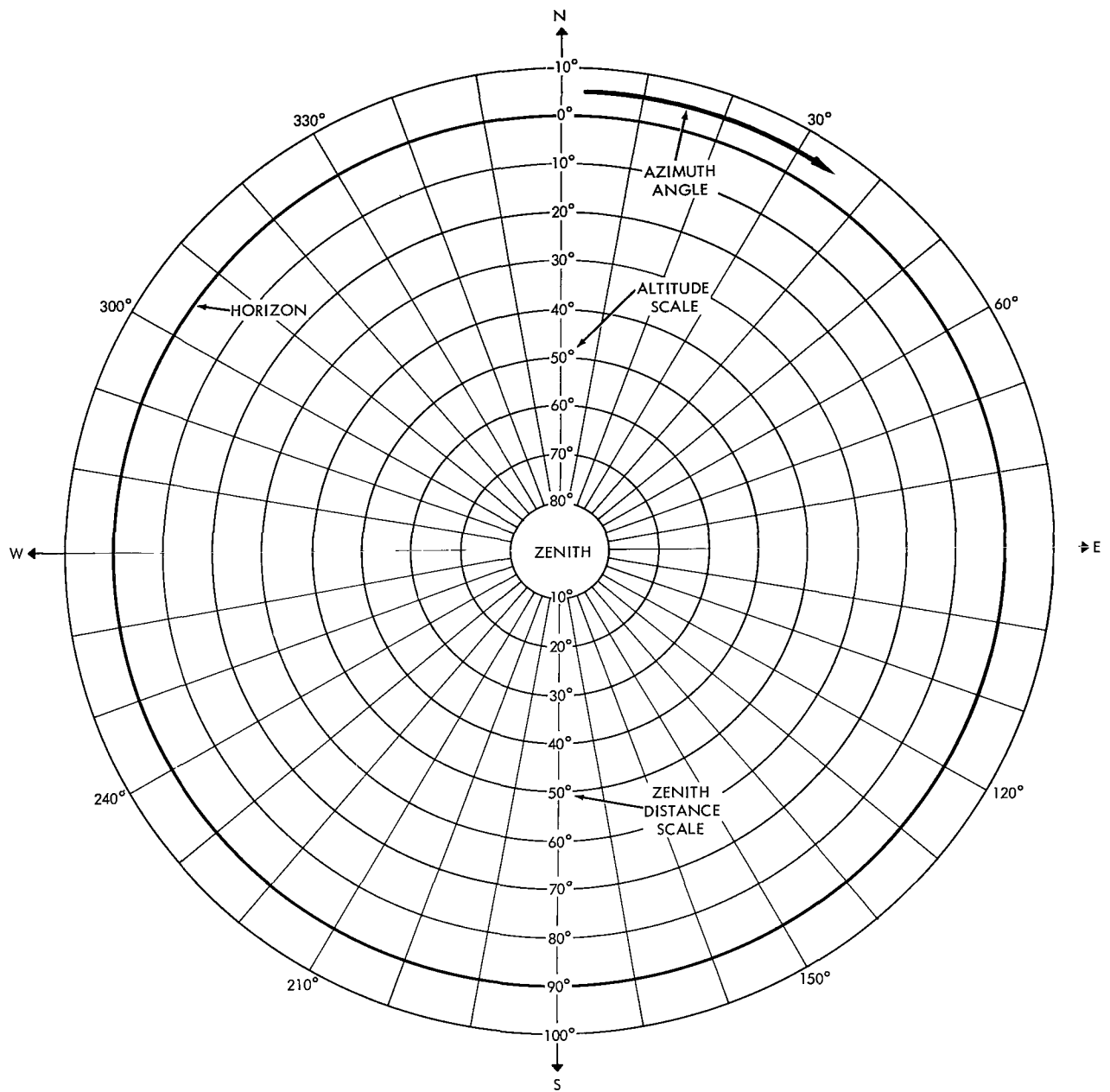


Figure 6—Plot of horizon system of coordinates.

the zenith in Figure 6. Any chosen radius, also called vertical circle, is therefore an azimuth angle with reference to north, and increments along this radius mark either the altitude or its complement, the zenith distance. This is done on translucent paper so that it may be viewed in combination with other transparencies on a light table.

The time, latitude, and longitude of the rocket flight are required for the location of the sun on the polar graph paper. For Nike-Apache shots, an average solar position is within the required

accuracy, but for longer and higher flights the trajectory should be divided into parts, and each successive time interval should specify a latitude and longitude to find the sun's altitude and azimuth. The sun's altitude and azimuth can be found by a large variety of celestial navigational techniques. This writer has found References 1 and 2 (see page 12) to be the best method. The magnetic south point, or flux vector, can be found from Reference 3 (page 12) as a function of latitude, longitude and altitude above the earth's surface.

In Figure 5 the azimuth of the rocket axis, R, is 249° , and its altitude is 52° . The azimuth of the sun, S, is 98° , and its altitude is 56° . The magnetic flux vector for White Sands Missile Range is marked M; it has an azimuth of 192° , and an altitude* of 60° (Reference 3). The zenith, Z, is directly over the center of gravity of the rocket. All of these coordinates have been transferred to identical positions in Figure 7.

In Figure 4, if concentric circles are drawn on the plastic hemisphere about the sun's 0° aspect angle point, S, then these circles will represent lines of equal solar aspect angle. Figure 8 is a zenith viewed *plot* of nine such equal solar aspect circles from 0° to 90° in 10° increments (in this example, the sun has an altitude of 35°).† Because of the nature of the plot, these circles appear as skewed ellipses. A rocket pointing at any one of these ellipses will have that solar aspect angle.

Similarly, equal magnetic aspect lines can be plotted as in Figure 9. In this particular case (White Sands Missile Range), the magnetic flux vector, M, has an altitude of 60° , and an azimuth of 192° (same as in Figure 7).

Now, if the solar and magnetic aspect-angle ellipses plotted in Figures 8 and 9 respectively, are plotted on transparent paper (each set of aspect angles on separate transparencies), then they can be superimposed on a polar coordinate system as shown in Figure 10. In this figure, the transparencies are incomplete ellipses of the solar aspect angles plotted for a sun altitude of 56° . The transparency is situated for the conditions under which Nike-Apache, Flight 14.363 GT was fired: the azimuth of the sun was 98° , and the magnetic flux vector was as outlined above (see Figure 9).

At this particular instant in the rocket's flight, the solar and magnetic aspect angles were 41° and 39° respectively. From Figure 10 the altitude of the vehicle is seen to be 80° (10° zenith distance), and the azimuth is 330° . The two phase lines drawn from the solar and magnetic transparencies thus show an angle of 75° .

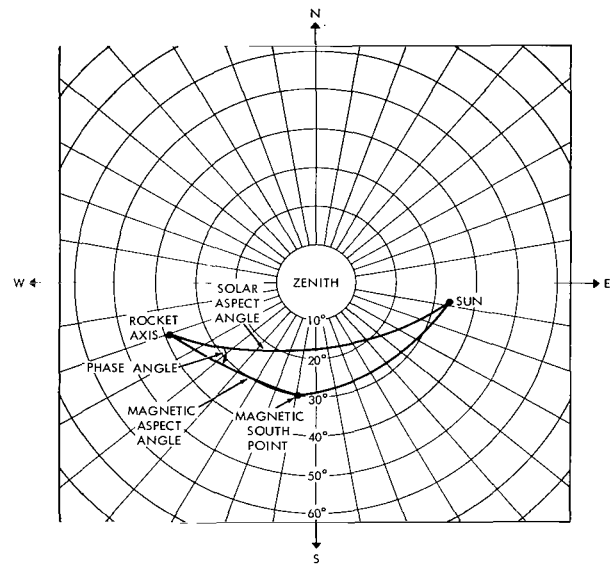


Figure 7—A plot of Figure 5.

*Appendix B explains altitude of the magnetic flux vector in terms of dip angle.

†The method of plotting these circles is outlined in Appendix A.

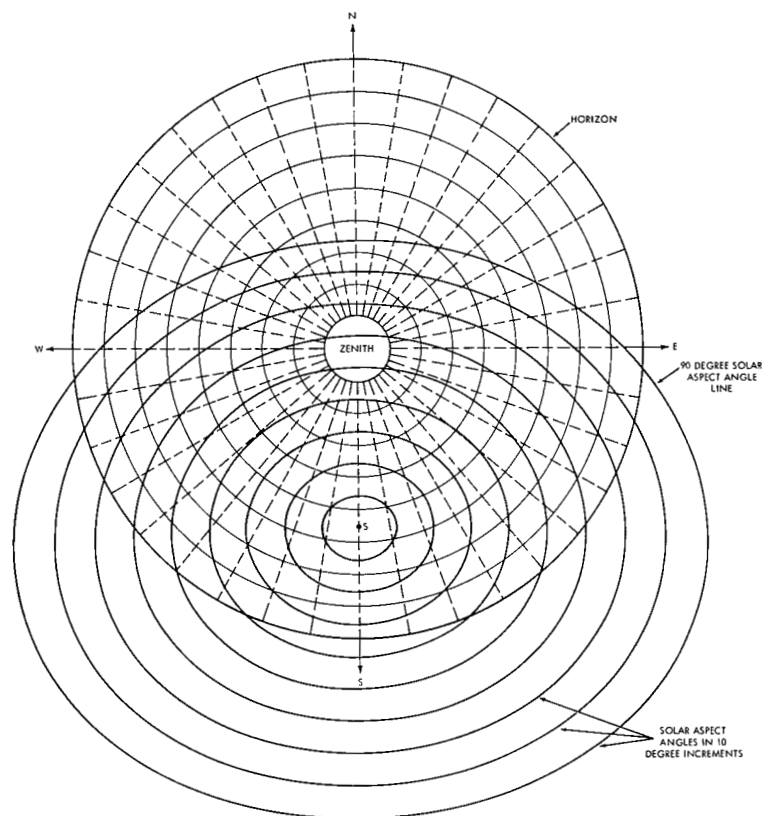


Figure 8—Nine solar aspect-angle ellipses for an altitude of 35° (shown at an azimuth of 180°).

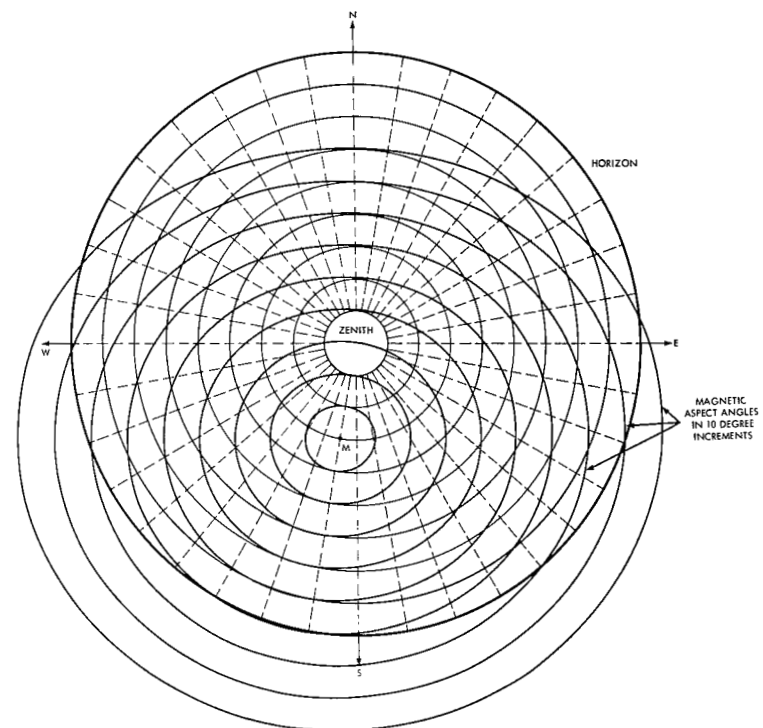


Figure 9—Nine aspect-angle ellipses corresponding to the magnetic aspect angles at White Sands Missile Range (60° altitude; 192° azimuth).

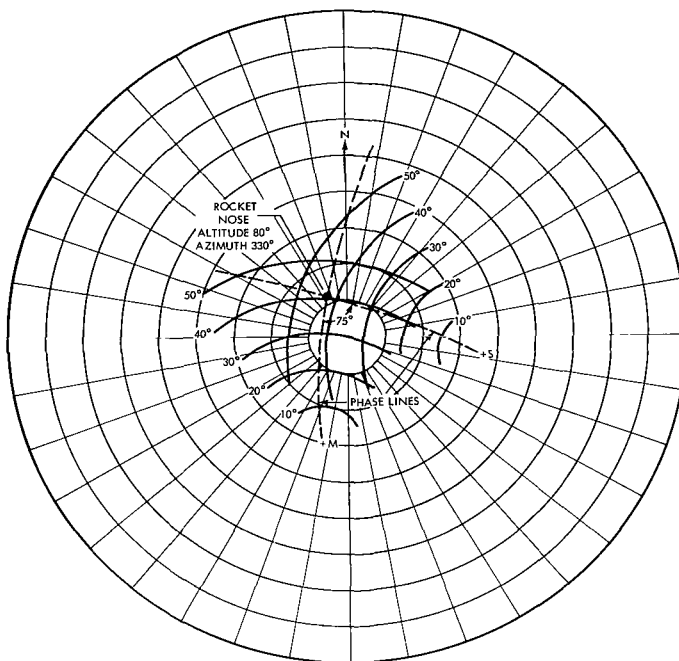


Figure 10—Superposition of partial solar and magnetic aspect-angle transparencies on polar coordinates to derive the values of rocket altitude, azimuth, and phase angle.

(Note: The transparencies of equal magnetic and solar aspect-angle lines are interchangeable for any given altitude.)

Instead of using telemetered solar and magnetic aspect angles, there is an alternate method of finding attitude based on the telemetered phase angle and solar aspect angle. This process will be apparent from Figure 11, where a 45° transparency (corresponding to the median rocket altitude at the telemetered solar aspect angle of 79°) has been placed with its center on the line representing the 79° aspect-angle line with respect to the sun. Since the phase angle has also been telemetered (39° , in this case), the transparency can be moved along the 79° ellipse until the phase angle between the sun and the magnetic south point becomes correct (39°). Care must be taken that the 45° transparency does not move into the 35° or 55° areas. The "radial" lines in the 45° transparency are two-dimensional plots of great circles on the original three-dimensional sky

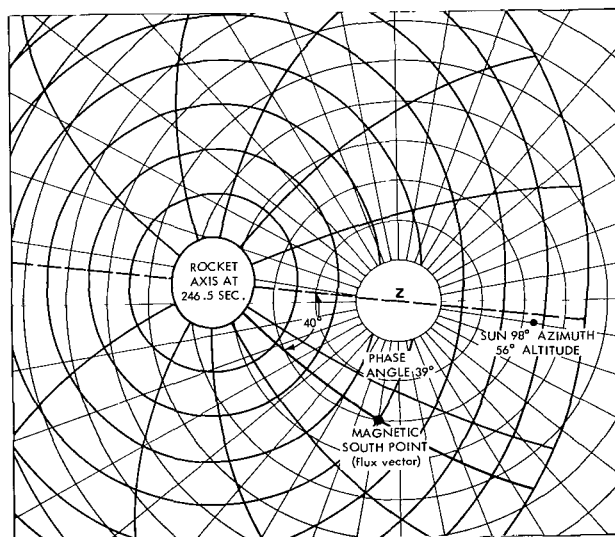


Figure 11—Transparency placed over rocket axis so that the sky can be mapped relative to the rocket.

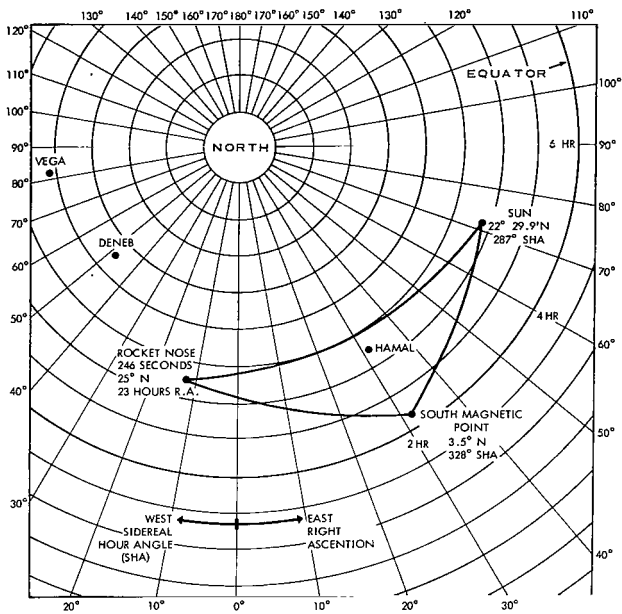


Figure 12—Use of celestial coordinate system.

model. (These radial lines, if employed with transparencies such as those of Figures 8, 9, and 10, constitute legs of phase angles between solar and magnetic aspect angles.)

This graphic method works equally well with the celestial coordinate system. This system is geocentric, its coordinates are: declination, right ascension, and sidereal hour angle.

In Figure 12 the sun, magnetic south point, and nose of the rocket are plotted with celestial coordinates. With the celestial system, the zenith is replaced by true north, altitude is replaced by declination, and azimuth is replaced by either sidereal hour angle or right ascension. Some of the stars have also been plotted. In this system the coordinates can be taken directly from a star almanac.

ACTUAL ANALYSIS OF A ROCKET FLIGHT

Nike-Apache, Flight No. 14.363 GT was fired from White Sands Missile Range on June 4, 1968. The NASA report, (Reference 3) gives the data. The Greenwich Mean Time, or Universal Time of firing was 16h,37m,28s. The peak altitude above the ground was 130 Km, or 80.8 statute miles.

The solar aspect angle of the rocket during its flight was taken from the telemetry record and plotted versus time. It was noted that from 70 seconds after lift-off to 244.75 seconds, the solar aspect angle varied sinusoidally from 38.5° to 45.0° at a constant period; from 244.75 seconds until atmospheric reentry it varied from 27° to 94° by another constant period. The magnetic aspect angles were measured and found to vary from maximum to minimum in precisely the same time periods.

The spin of the vehicle was measured using the solar aspect signal during early and late flight and found to be a constant 9.09 cycles per second. The solar aspect sensor signals more precisely define the time than the lateral magnetometer signals. The total angular momentum of the vehicle is divided between the spin and cone periods, and a change in one means a change in the other for a constant mass.

The solar aspect angle versus time was plotted from 30 seconds after lift-off to 330 seconds as shown in Figure 13. Note that from 70 seconds until 244.75 seconds, the variation is sinusoidal. A phase relationship with the maximum and minimum magnetic aspect angles was established, and by plotting these positions it was found that the vehicle coned six times about a momentum vector of altitude 80° and azimuth 320° . The cone angle was 6.5° and the period was 32.72 seconds.

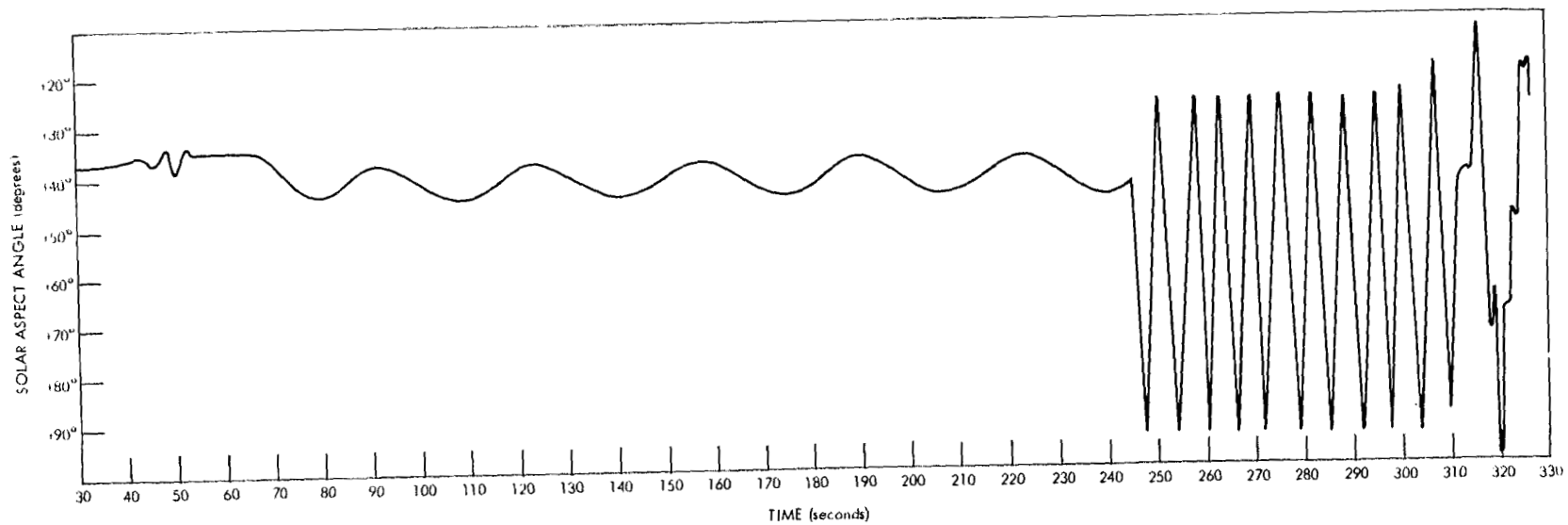


Figure 13—Solar aspect angle as a function of time for flight 14.363.

During the early part of the flight, from 20 to 95 seconds, the change in latitude and longitude indicated, through the radar plots, the velocity vector. The velocity vector during the powered portion of the flight is the average attitude of the vehicle. From this portion of the flight, the phase angle between the sun and magnetic south point was checked. This confirms the placement of the solar aspect sensors and of the magnetometers within the payload.

At 244.75 seconds, as noted in Figure 13, the second stage was separated* from the payload and the solar aspect angle began to vary sinusoidally from 27° to 94° . The period of the new cone was found to be 6.25 seconds, and the coning angle was about 67° about a new momentum vector. The new momentum vector's altitude was 60° , and its azimuth was 229° . It coned 10 times about this new vector before reentry into the atmosphere.

At 259 seconds after lift-off, 50 solar signals were counted on the telemetry record, as were 50 magnetic aspect maximum signals on the lateral magnetometer. It was noted that 51 solar aspect signals coincided with 50 magnetometer maximums. The loss of one magnetometer maximum signal is due to the fact that the vehicle coned once around the magnetic south point in the same interval. Had the vehicle coned outside the magnetic south point the number of corresponding solar and magnetic signals would coincide.

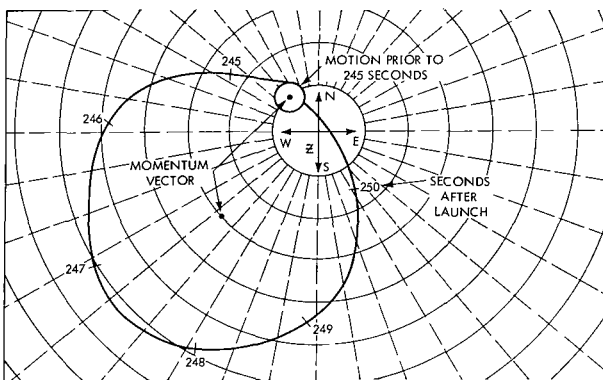


Figure 14—The epicycloidal motion of flight 14.363 GT immediately before and after change in momentum vector.

In the manner of Figure 10, a succession of positions were plotted for the solar and magnetic aspect angles for both early and late flight. The result of plotting these points is shown in Figure 14. The two circles represent the epicycloidal motion immediately before and after ejection of the second stage and the consequent change in the momentum vector.

In Figure 11, the 45° transparency (corresponding to the rocket's altitude) has been placed with its center directly over the nose position at 246 seconds after lift-off.

At this time, the rocket's altitude is about 45° and the azimuth is 276° . The rest of the sky, as seen from the rocket nose, can now be mapped by this transparency; and the aspect angle between the vehicle and the azimuth and altitude of any other celestial body can be plotted.

FORTTRAN CORROBORATION OF GRAPHIC METHOD

Table 1 shows some of the input and output values of a FORTRAN program for computing the attitude of a rocket vehicle. The input was telemetered data of magnetic and solar aspect angles.

*At 244.75 seconds after lift-off, the payload and recovery system were separated from the second stage.

Table 1

Partial Results of FORTRAN Analysis of Nike-Apache, Flight 14.363 GT.

FORTRAN Input			Output		
Flight Time (sec.)	Solar Aspect Angle (degrees)	Magnetic Aspect Angle (degrees)	Zenith Distance of Rocket Nose (degrees)	Azimuth of Rocket Nose (degrees)	Phase Angle (degrees)
156	38.5	36.6	7.75	337.02	79.10
157	38.5	36.8	7.91	337.07	78.90
158	38.6	37.3	8.36	339.57	78.28
159	38.8	38.0	9.01	341.23	77.37
160	39.1	38.6	9.63	341.80	76.48
161	39.7	39.3	10.45	341.10	75.24
162	40.0	39.7	10.9	340.97	74.59
163	40.6	40.1	11.47	339.42	73.70
164	41.2	40.5	12.05	338.01	72.82
165	41.8	40.7	12.48	336.03	72.14
166	42.5	40.8	12.89	333.40	71.46
167	43.1	40.8	13.20	330.95	70.95
168	43.6	40.6	13.34	328.27	70.66
169	44.2	40.4	13.56	325.25	70.27
170	44.6	40.1	13.62	322.66	70.12
171	44.8	39.6	13.46	320.03	70.26
172	45.0	39.2	13.38	317.76	70.32
173	45.0	38.6	13.06	315.34	70.69
174	45.0	38.0	12.77	312.82	71.07
175	44.8	37.4	12.34	310.89	71.65
176	44.5	37.7	12.25	313.26	71.76
177	44.0	36.0	11.11	307.05	73.42
178	43.6	35.6	10.62	306.41	74.15
179	43.0	35.1	9.93	305.87	75.21
180	42.3	34.7	9.20	306.20	76.36
181	41.8	34.4	8.66	306.34	77.21
182	41.1	34.3	8.05	308.67	78.17
183	40.5	34.3	7.57	311.47	78.93
184	40.0	34.4	7.23	314.73	79.47
185	39.5	34.6	6.97	318.94	79.90
186	39.1	34.9	6.88	323.43	80.11
187	38.7	35.3	6.90	328.61	80.20
188	38.6	35.7	7.12	331.64	79.91
189	38.5	36.4	7.60	336.04	79.31
190	38.5	37.0	8.07	338.88	78.69
191	38.6	37.5	8.25	340.42	78.08

The input values from telemetry were not to this degree of accuracy, but were used to demonstrate the correlation of the graphic and FORTRAN methods.

The output values should be rounded off to the nearest degree to conform with the order of accuracy. Although magnetometers and solar aspect sensors are carefully calibrated, the order

of accuracy may be degraded by telemetry and by recording techniques.

Figure 15 shows a comparison of the values from Table 1 and the data taken from the graphic analysis. More extensive corroboration has been completed using the same program and cycling both the solar and magnetic aspect angles in 15° increments (from 15° to 165°). Graphic and FORTRAN values agree to within 2° .

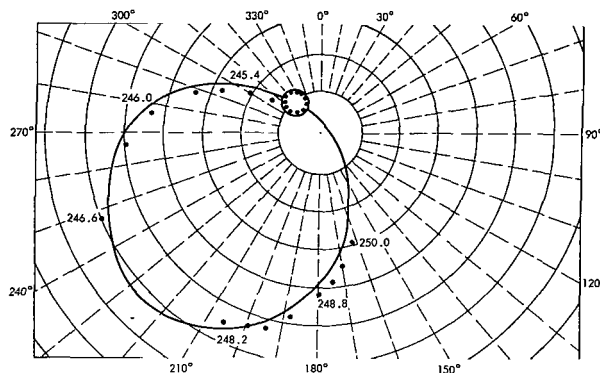


Figure 15—Comparison of graphic method (solid lines) and FORTRAN corroboration (dots).

ASPECT-PHASE SET AND POLAR PAPER TRANSPARENCIES

There are nine aspect angle and phase angle coordinate charts, or transparencies available for each 10° of altitude from 5° to 85° . There is also one polar graph paper transparency.

Each chart for each respective altitude of the reference point, either the sun or magnetic south, plots the aspect angle and phase angle with respect to the zenith point. The polar paper provides either altitude or azimuth coordinates of the axis of the vehicle in the horizon system, or declination or right ascension coordinates in the celestial system.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, September 24, 1968
879-70-01-03-51

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3. Cain, J. C., Hendrick, S., Daniels, W. E., and Jensen, D. C., "Computations of the Main Geomagnetic Field from Spherical Harmonic Expansion," Data Users Note NSFDC-68-11 May, 1968; formerly NASA-GSFC Document X-611-64-316, 1964.
4. NASA Report of Sounding Rocket Launching Vehicle No.: 14.363; Rocket type: Nike-Apache; Launching Site: White Sands, New Mexico; Range No.: CA-1; NASA Project Scientist: James F. Wood.
5. Bowditch, N., "American Practical Navigator," U. S. Navy Hydrographic Office, corrected reprint, 1962.

Appendix A

DERIVATION OF EQUAL ASPECT-ANGLE TRANSPARENCIES

Two standard trigonometric formulas can be used to locate points along each equal aspect-angle ellipse. They are (Reference 5)

$$\cos t = \frac{\sin\left(\frac{\pi}{2} - a\right) - \sin L \sin d}{\cos L \cos d}, \quad (\text{A1})$$

and

$$\sin Z = \cos d \sin t \sec\left(\frac{\pi}{2} - a\right), \quad (\text{A2})$$

where the terms are defined in Figure A1.

In the Figure A1, A and B are two points which the above equations can locate on the equal aspect-angle ellipse having an aspect angle, a . (In the figure, the sun is used as the datum for the ellipses. The plotting of magnetic equal aspect-angle ellipses is the same, except that the magnetic flux point vector is used. In fact, the ellipses for either the solar or magnetic cases are interchangeable.)

When plotting the ellipse for a given aspect angle, a , the sun's altitude, L , and an arbitrary altitude, d (to point B) can be inserted into Equation A1 to find an angle t .

The angle t , the local hour angle (LHA), is then added to the sun's azimuth to locate A, and subtracted to locate B. In a strict sense the angle, t , is a meridian angle. Thus two points, A and B, of the given ellipse are found in terms of the altitude, and azimuth relative to the sun.

Alternatively, Equation A2 gives

$$\sin t = \frac{\sin Z}{\cos d \sec\left(\frac{\pi}{2} - a\right)}. \quad (\text{A3})$$

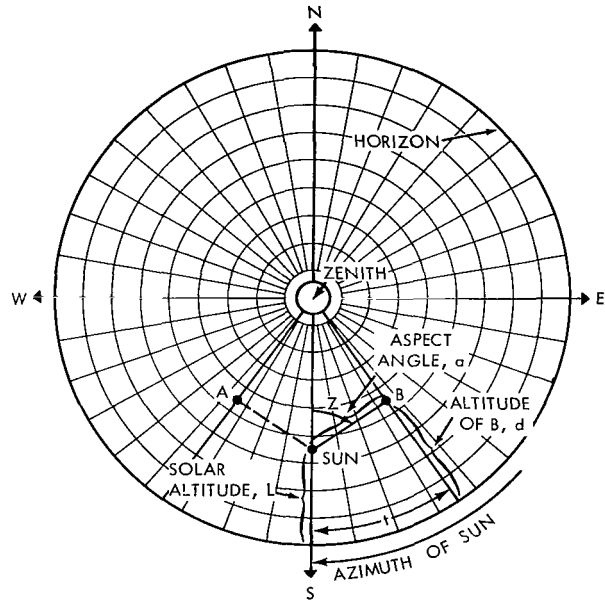


Figure A1—Terms used to plot equal aspect-angle ellipses.

Angle Z, aspect angle, a, and altitude, d, of the given point B, thus yields a value for t. A and B are thus again located for the ellipse of equal aspect angle, a.

In the transparency plots, five-degree increments of altitude and azimuth were chosen for each value of L.

To avoid some lengthy calculations the following FORTRAN program was used:

RAN IV G LEVEL 1, MOD 2 MAIN DATE = 68282 22/50/05

```

C      GRAPHIC ATTITUDE METHOD COORDINATES
      RAD=57.295779
      WRITE(6,50)
50  FORMAT('1')
      DO 100 I= 5,85,10
      DO 100 J= 10,90,5
      DO 100 K= 5,175,5
      ZS=I/RAD
      RS=J/RAD
      S=K/RAD
      CALL CAAAB(ZS,S,RS,ZR,Z)
      ZR=ZR*RAD
      Z=Z*RAD
      WRITE(6,95)I,J,K,ZR,Z
95  FORMAT(' ',3I7,2F12.3)
100 CONTINUE
      STOP
      END

```

Zenith Distance, ZS, of the Sun, was cycled from 5° to 85° in steps of 5. Solar aspect angle, RS, from the sun to the rocket, was cycled from 10° to 90° in steps of 5. Angle S at the sun between ZS and RS, was cycled from 5° to 175° in steps of 5.

A spherical triangle subroutine of side-angle-side, solved the triangle for remaining side and angles. The output, in terms of ZR, the zenith distance of the rocket axis, and the angle SZR between ZS and ZR, was tabulated for each combination of solar aspect angles, and angle S.

RAN IV G LEVEL 1, MOD 2 CAAAB DATE = 68282 22/50/05

```

      SUBROUTINE CAAAB(CA,A,AB,BC,C)                      0000010
C SAS SPHERICAL TRIANGLE SOLVER. CA,A,AB ARE SIDE,ANGLE,SIDE INPUT. 0000011
C OUTPUT ARE BC = THIRD SIDE AND C = ANGLE OPPOSITE AB.                      0000012
C INPUT AND OUTPUT ALL IN RADIANS.                      0000013

```

RAN IV G LEVEL 1, MOD 2

CAAAB

DATE = 68282

22/50/05

COSCA = COS(CA)	0000020
SINCA = SIN(CA)	0000030
COSAB = COS(AB)	0000040
SINAB = SIN(AB)	0000050
COSBC = COSCA*COSAB + SINCA*SINAB*COS(A)	0000060
SINBC = SQRT(1.-COSBC*COSBC)	0000070
BC = 1.5707963 - ATAN(COSBC/SINBC)	0000080
SINC = SINAB * SIN(A) / SINBC	0000090
COSC = (COSAB-(COSBC*COSCA)) / (SINBC*SINCA)	0000100
C = 3.1415927 - ATAN2(SINC,-COSC)	0000110
RETURN	0000115
END	0000120

Appendix B

MAGNETIC FIELD: VARIATION AND DIP ANGLE

The direction and magnitude of the magnetic flux vector varies widely depending on the location on or near the earth. The true north, represented by the axis of rotation of the earth, is compared with the magnetic north point. The simplest way of considering the earth's field is to say that the north magnetic pole is buried near the north pole. Therefore a magnetically balanced needle would have two components, a horizontal component called variation, and a dip called dip angle. The variation is the number of degrees which the needle points east or west of true north. The dip angle is due to the fact that the north seeking end is pointed downward toward the buried pole. At White Sands Missile Range the variation is 12° east, which means that the southern end of the needle has a $180^\circ + 12^\circ$ or 192° azimuth. The dip angle is 60° , which means that the south magnetic point has an altitude of 60° .

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